

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE Technical Paper		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE  <i>Please see attached</i>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
				5d. PROJECT NUMBER 4847	
6. AUTHOR(S)				5e. TASK NUMBER 0052	
				5f. WORK UNIT NUMBER 549927	
				8. PERFORMING ORGANIZATION REPORT	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  ERC				10. SPONSOR/MONITOR'S ACRONYM(S)	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)  Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048				11. SPONSOR/MONITOR'S NUMBER(S) <i>Please see attached</i>	
12. DISTRIBUTION / AVAILABILITY STATEMENT  Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
20030205 166					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	<i>A</i>		Leilani Richardson
Unclassified	Unclassified	Unclassified			19b. TELEPHONE NUMBER (include area code) (661) 275-5015

99 C0025 488786 52

MEMORANDUM FOR PRS (In-House Contractor Publication)

FROM: PROI (STINFO)

17 May 2002

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-VG-2002-114**  
David Kirtley (ERC) and John Fife (PRSS), "Modeling, Simulation, and Design of an Electrostatic Colloid Thruster" (Viewgraphs only)

**29<sup>th</sup> IEEE International Conference on Plasma Science**  
**(Banfe, Alberta, Canada) (Deadline: 26 May 2002)**

**(Statement A)**

1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement, b.) military/national critical technology, c.) export controls or distribution restrictions, d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.

Comments: \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

Signature \_\_\_\_\_ Date \_\_\_\_\_

2. This request has been reviewed by the Public Affairs Office for: a.) appropriateness for public release and/or b) possible higher headquarters review.

Comments: \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

Signature \_\_\_\_\_ Date \_\_\_\_\_

3. This request has been reviewed by the STINFO for: a.) changes if approved as amended, b) appropriateness of references, if applicable; and c.) format and completion of meeting clearance form if required

Comments: \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

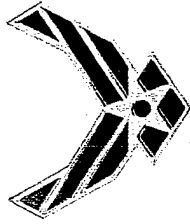
Signature \_\_\_\_\_ Date \_\_\_\_\_

4. This request has been reviewed by PR for: a.) technical accuracy, b.) appropriateness for audience, c.) appropriateness of distribution statement, d.) technical sensitivity and economic sensitivity, e.) military/national critical technology, and f.) data rights and patentability

Comments: \_\_\_\_\_  
\_\_\_\_\_

APPROVED/APPROVED AS AMENDED/DISAPPROVED

\_\_\_\_\_  
PHILIP A. KESSEL Date  
Technical Advisor  
Space and Missile Propulsion Division



# **Modeling, Simulation, and Design of an Electrostatic Colloid Thruster**

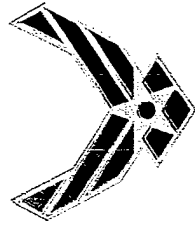
David Kirtley

J. M. Fife

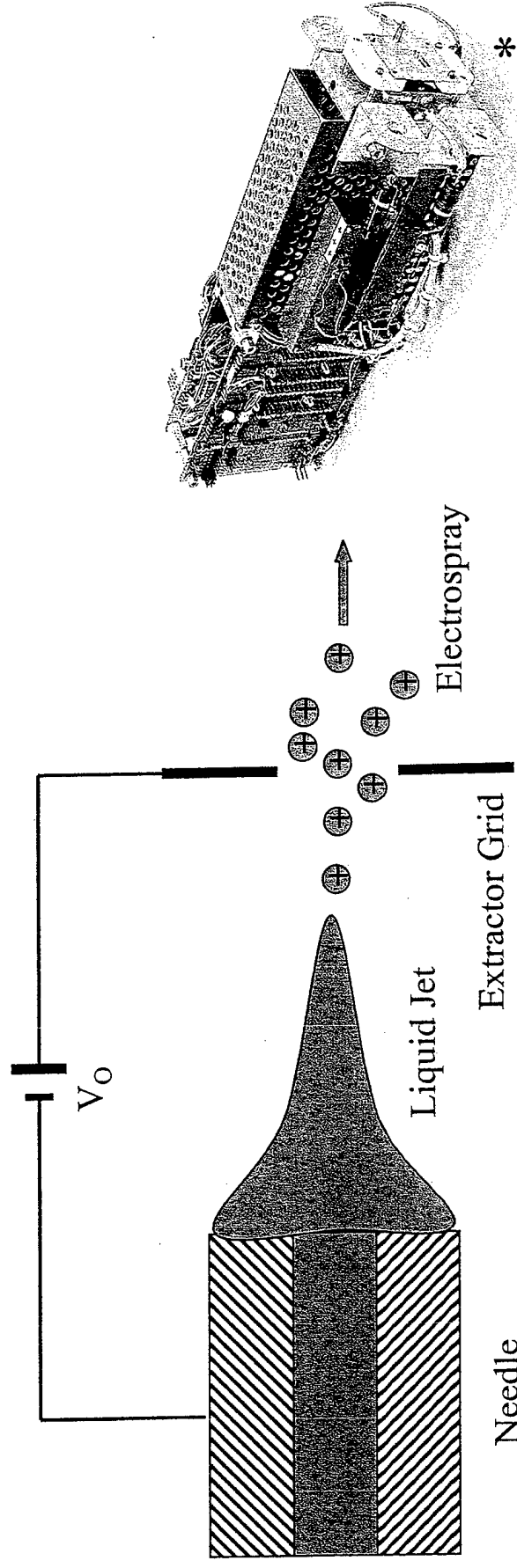
28 May 2002



- Colloid Introduction
- Design Process
  - OTS Modeling, Simulation
- Particle Tracking Analysis
- Non-Ideal Acceleration Voltages
  - Turn-On, Turn-Off, Dispersion, Off-Axis
- Preliminary Extraction Models
- Performance Optimization



# Colloid Introduction



## •Colloid Engine Theory:

- Particles with Large mass/charge enable higher thrust density Ion (electrostatic) engines
- Use electric fields to extract charged high-conductivity liquid droplets (electro-spray)
- Accelerate particles at high velocities (up to 1500s) and high efficiency (to 90%)
- Arrays of small needles that each provide small thrust ( $\mu\text{N's}$ ) with capillary feed systems
- No sheath/ionization losses/complications

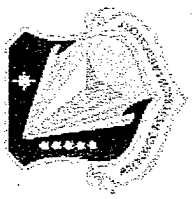


# Design Thrusters, Not Electrospray

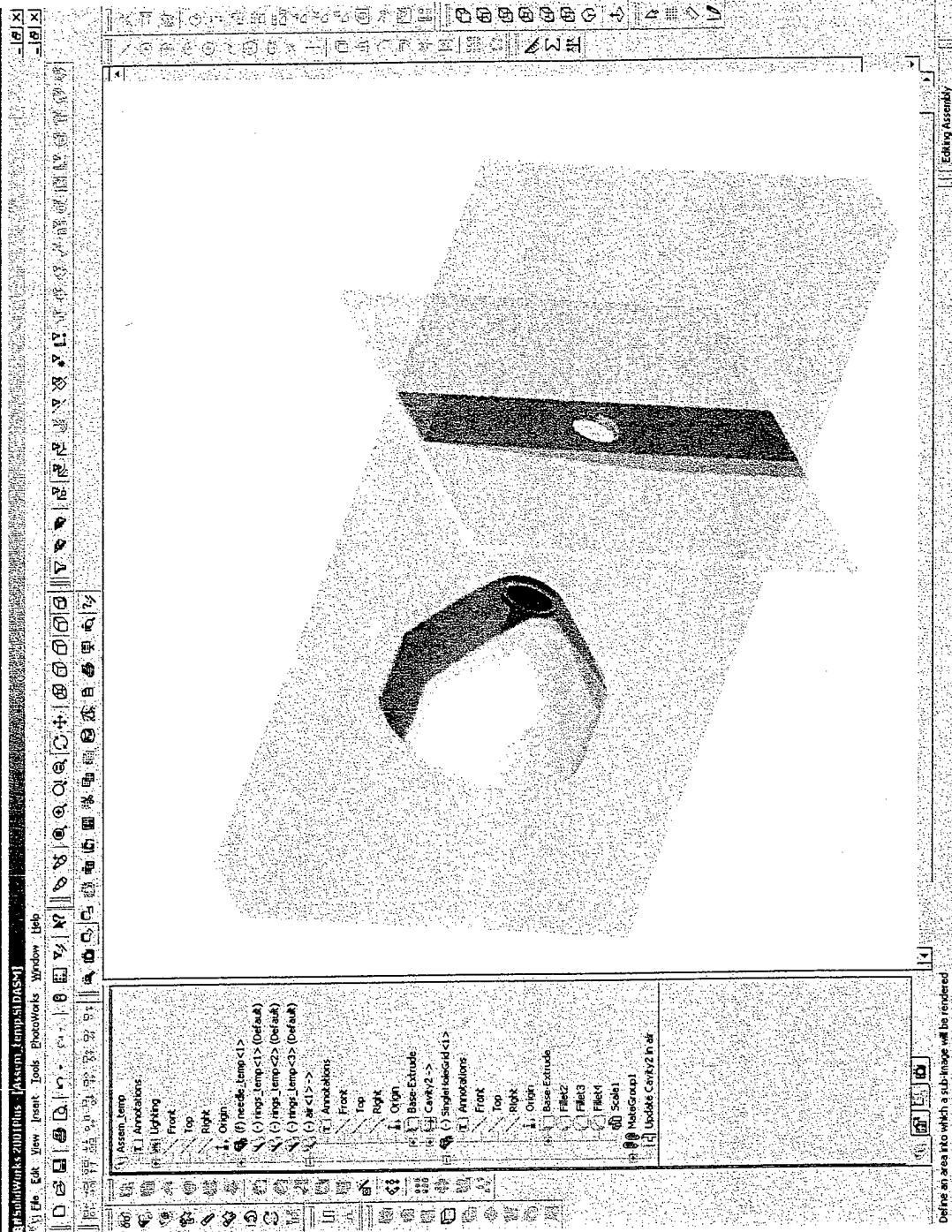
- 
- The figure consists of two line graphs. The top graph plots Thrust (N) on the y-axis (0.00E+00 to 5.00E-06) against q/m on the x-axis (0 to 25000). The bottom graph plots Time (s) on the y-axis (0 to 1600) against q/m on the x-axis (0 to 20000). Both graphs show four curves for different volumes: V=500, V=1000, V=2000, and V=5000. In the top graph, Thrust increases with q/m for all volumes, with higher volumes resulting in higher thrust values. In the bottom graph, Time increases with q/m for all volumes, with higher volumes resulting in longer times.
- Top Graph: Thrust (N) vs q/m**
- | q/m   | V=500 (N) | V=1000 (N) | V=2000 (N) | V=5000 (N) |
|-------|-----------|------------|------------|------------|
| 0     | 0.00E+00  | 0.00E+00   | 0.00E+00   | 0.00E+00   |
| 5000  | ~1.5E-06  | ~2.0E-06   | ~2.5E-06   | ~3.0E-06   |
| 10000 | ~3.0E-06  | ~4.0E-06   | ~5.0E-06   | ~6.0E-06   |
| 15000 | ~4.5E-06  | ~6.0E-06   | ~7.5E-06   | ~9.0E-06   |
| 20000 | ~6.0E-06  | ~8.0E-06   | ~1.0E-05   | ~1.2E-05   |
| 25000 | ~7.5E-06  | ~1.0E-05   | ~1.2E-05   | ~1.5E-05   |
- Bottom Graph: Time (s) vs q/m**
- | q/m   | V=500 (s) | V=1000 (s) | V=2000 (s) | V=5000 (s) |
|-------|-----------|------------|------------|------------|
| 0     | 0         | 0          | 0          | 0          |
| 5000  | ~200      | ~400       | ~600       | ~800       |
| 10000 | ~400      | ~800       | ~1200      | ~1600      |
| 15000 | ~600      | ~1200      | ~1800      | ~2400      |
| 20000 | ~800      | ~1600      | ~2400      | ~3200      |
| 25000 | ~1000     | ~2000      | ~3000      | ~4000      |



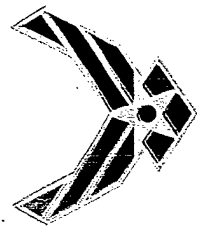
# Off-The-Shelf Modeling, Simulation



Use OTS 3D  
Modeling, Grid  
Generation,  
Electrostatic Solvers to  
speed/cheapen thruster  
design and simulation



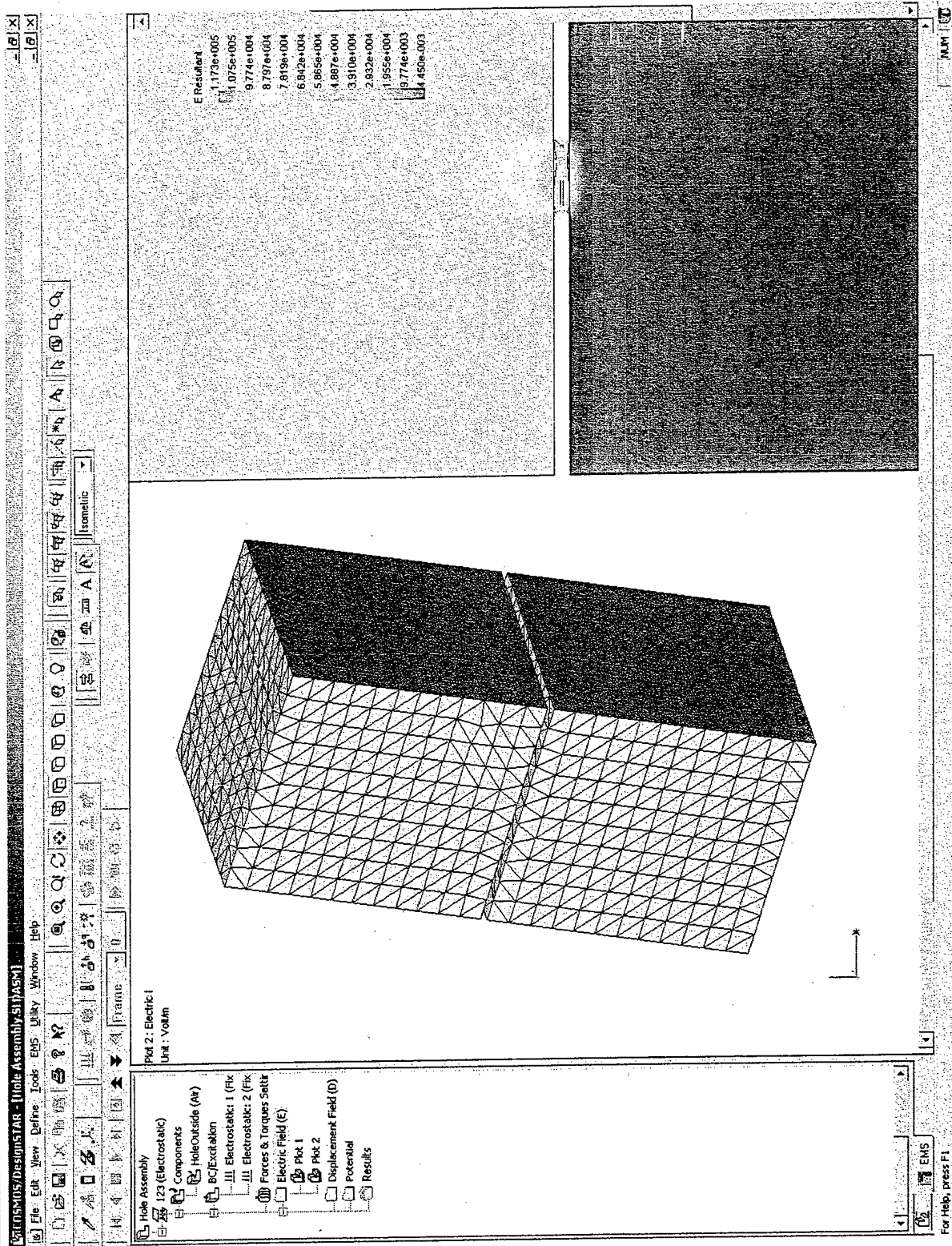
SOLIDWORKS COLLOID  
MODEL



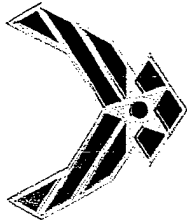
# Off-The-Shelf Modeling, Simulation



## COSMOSWORKS EMS Gridding





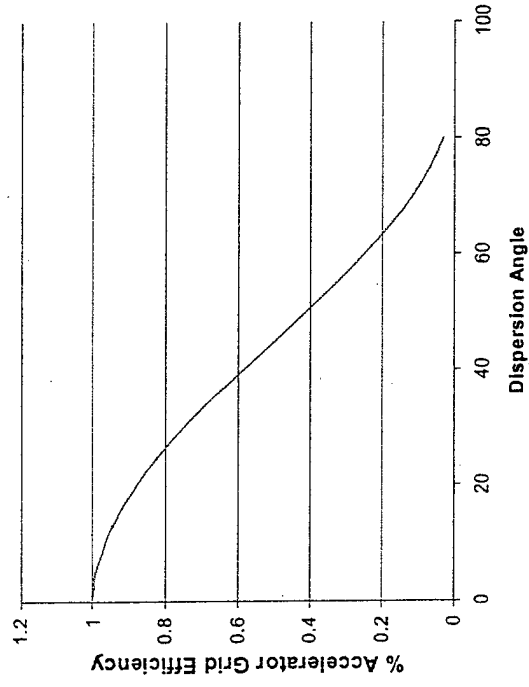
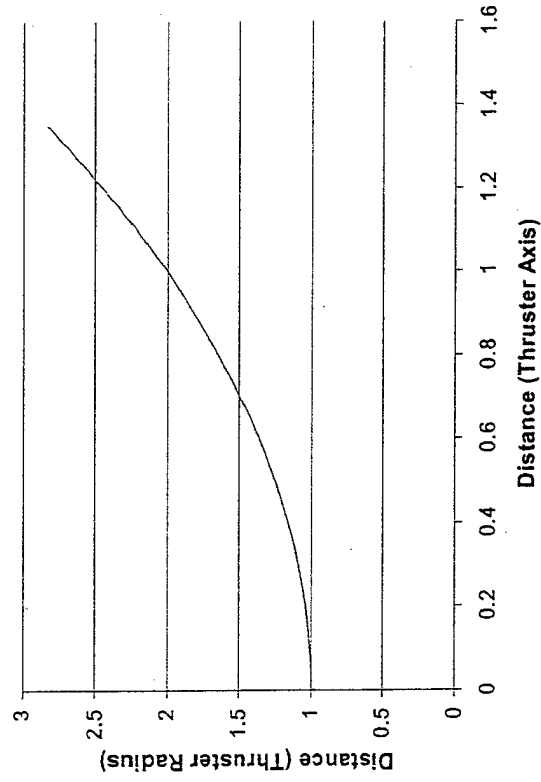


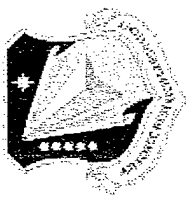
# Particle Tracking Analysis



- Straight Dispersion Prediction
- E-field shaping models
- Acceleration/Efficiency losses due to non-uniform E-fields, grids

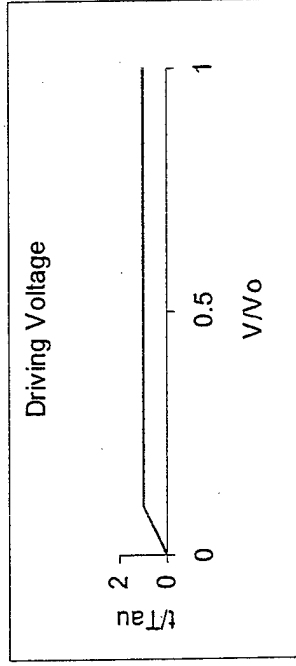
Dispersion Path





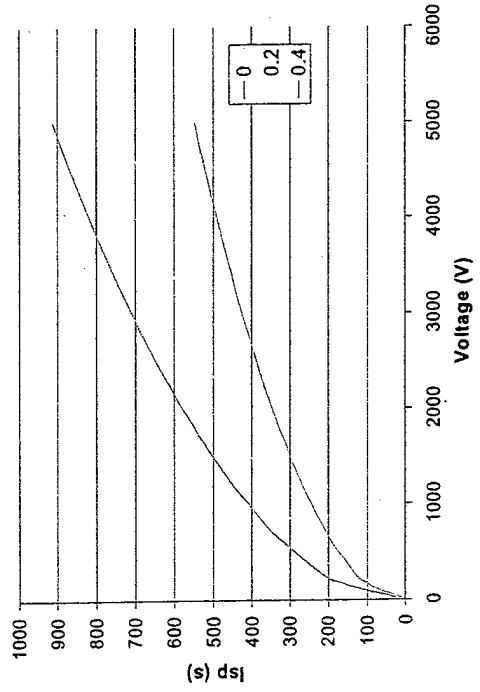
# Performance Losses

- Turn-On, single droplet



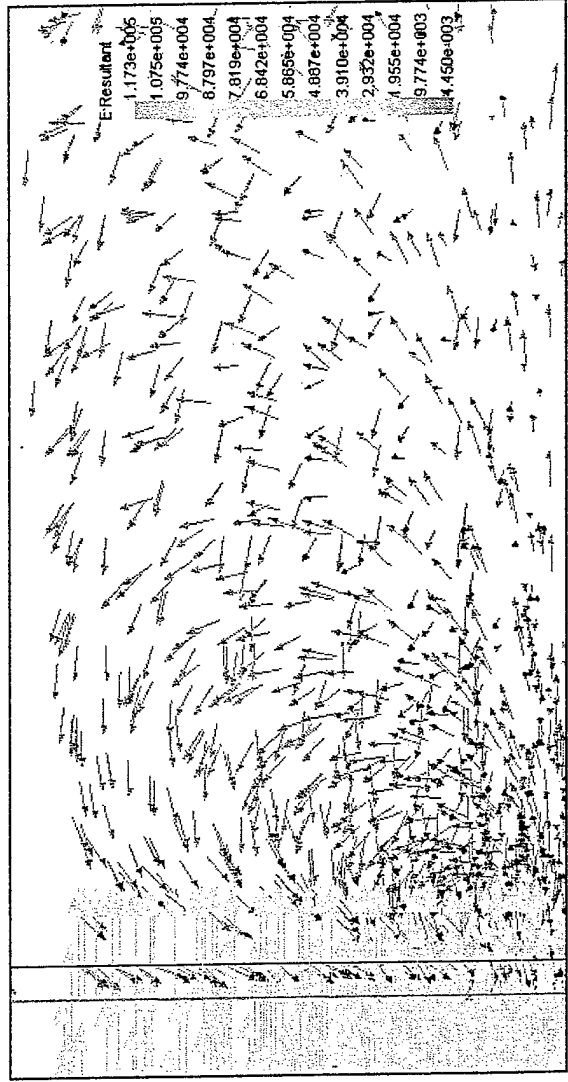
$$x(t) = \frac{q}{m} \Delta x \left( M t_{rise}^2 * t + V \left( \frac{t^2}{2} - t * t_{rise} \right) \right)$$

Isp-V as a function of Rise Time



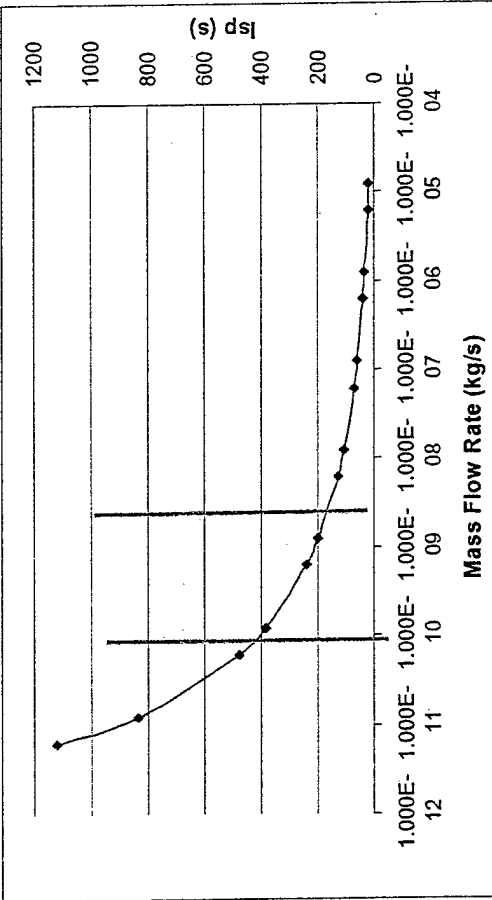
- E-field Incongruities at Interface

- Highly situation dependent
- Developed analysis system for individual cases





# Extractor Modeling

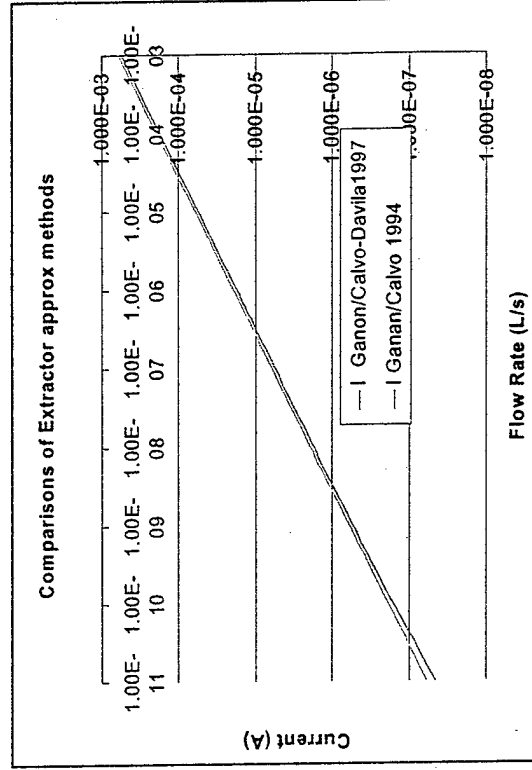
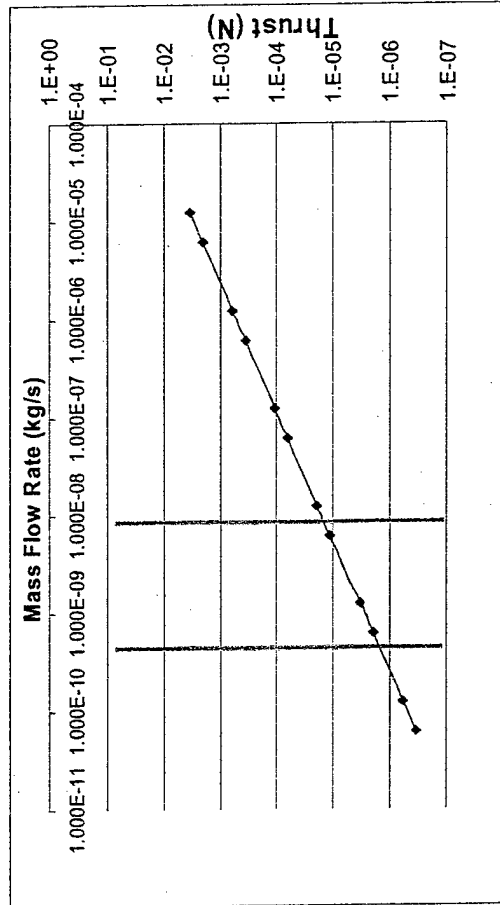


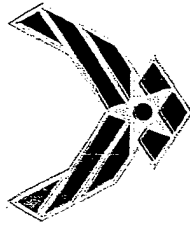
Ganan-Calvo 1997, 1994

De La Mora and Loscertales 1993

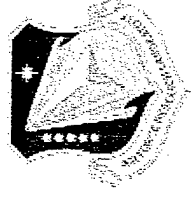
$$\frac{I}{I_0} = 6.2 \left[ \frac{Q}{(\beta - 1)^{1/2} Q_0} \right]^{-2.0}$$

$$\frac{d}{d_0(\beta - 1)^{1/3}} = 1.6 \left[ \frac{Q}{(\beta - 1)^{1/2} Q_0} \right]^{-1.0}$$





## Conclusion



- Presented is a modeling design process for a colloid micro-thruster
- Acceleration Grid Effects
- Extractor Grid Effects
- Performance Predicting, Optimization



# References



- \*Stanford Colloid Micro-Thrusters, Prof. Mark Cappelli et al.
- Ganan-Calvo, A.M. et al. Current and Droplet size in the Electrospaying of liquids. Scaling laws. 1996
- Chen and Pui. Experimental Investigation of Scaling Laws for Electrospaying: Dielectric Constant Effect. Aerosol Science and Technology, 1997.
- Gamero-Castano and Hruby. Electrospray as a Source of Nanoparticles of Efficient Colloid Thrusters. Journal of Propulsion and Power, 2001.
- De la mora and Loscertales. The current emitted by highly conducting Taylor cones. Journal of Fluid Mechanics, 1994.
- Cloupeau and Prunet-Foch. Electrohydrodynamic-spraying functioning modes: a critical review. Journal of Aerosol Sciences, 1994.